

The first observation of $\tau^\pm \rightarrow \phi K^\pm \nu$ decay

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Abstract

We present the first measurement of tau-decays to hadronic final states with a ϕ -meson. This is based on 401.4 fb^{-1} of data accumulated at the Belle experiment. The branching ratio obtained is $B(\tau^\pm \rightarrow \phi K^\pm \nu) = (4.06 \pm 0.25 \pm 0.26) \times 10^{-5}$.

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INTRODUCTION

While hadronic τ^\pm decays with a ϕ meson in the final state are valuable to investigate QCD at a low mass scale, they have never been observed due to their small branching fractions. The decay $\tau^\pm \rightarrow \phi K^\pm \nu$ is Cabibbo suppressed and further restricted by its small phase space, while the decay $\tau^\pm \rightarrow \phi \pi^\pm \nu$ is suppressed by the OZI rule although it is Cabibbo allowed. Taking into accounts differences in Cabibbo mixing effects and phase space relative to the Cabibbo allowed transition $\tau^\pm \rightarrow K^{0*} K^\pm \nu$, the branching fraction for $\tau^\pm \rightarrow \phi K^\pm \nu$ is estimated to be $B(\tau^\pm \rightarrow \phi K^\pm \nu) = 2 \times 10^{-5}$ [1]. On the other hand, the vector dominance model predicts $B(\tau^\pm \rightarrow \phi \pi^\pm \nu) = (1.20 \pm 0.48) \times 10^{-5}$ [2].

CLEO searched for these decays using 3.1 fb^{-1} of data taken on $\Upsilon(4S)$ resonance. They set upper limits of $B(\tau^\pm \rightarrow \phi K^\pm \nu) < (5.4 - 6.7) \times 10^{-5}$ and $B(\tau^\pm \rightarrow \phi \pi^\pm \nu) < (1.2 - 2.0) \times 10^{-4}$ at the 90% confidence level [1]. Here we report the first measurement of $\tau^\pm \rightarrow \phi K^\pm \nu$ and $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ decays. These results are based on a data sample of 401.4 fb^{-1} corresponding to $3.6 \times 10^8 \tau^+ \tau^-$ pairs collected near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+ e^-$ (3.5 on 8 GeV) collider [3]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [4]. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector was used for the first sample of 157.7 fb^{-1} , while a 1.5 cm beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining 243.7 fb^{-1} [5].

While the decay $\tau^\pm \rightarrow \phi \pi^\pm \nu$ is also interesting, it is treated here as a background process including the kinematically allowed but phase-space suppressed decays of $\tau^\pm \rightarrow \phi(n\pi)\nu$ ($2 \leq n \leq 5$).

EVENT SELECTION

We look for $\tau^\pm \rightarrow \phi K^\pm \nu$ candidates in $e^+ e^- \rightarrow \tau^+ \tau^-$ reaction in the following modes.

$$\begin{aligned} \tau_{\text{signal}}^\pm &\rightarrow \phi + K^\pm + (\text{missing}) \\ &\hookleftrightarrow K^+ K^- \\ \tau_{\text{tag}}^\mp &\rightarrow (\mu/e)^\mp + n(\leq 1)\gamma + (\text{missing}) \end{aligned}$$

The detection of ϕ -mesons relies on the $\phi \rightarrow K^+ K^-$ decay ($B = (49.1 \pm 0.6)\%$); the final evaluation of the signal yield is carried out using the $K^+ K^-$ invariant mass distribution.

Selection criteria described below are determined, based on examinations of Monte-Carlo (MC) events. The background samples consist of $\tau\tau$ (1570.0 fb^{-1} , which does not include any decay-mode with a ϕ meson) and other backgrounds such as $q\bar{q}$ continuum, $B^0 \bar{B}^0$, $B^+ B^-$ and two-photon processes. For signal, we generate samples with $1 \times 10^6 \tau^\pm \rightarrow \phi K^\pm \nu$, $\phi K^\pm \pi^0 \nu$, $\phi \pi^\pm \nu$ and $\phi \pi^\pm \pi^0 \nu$.

Transverse momentum (p_t) for a charged track is required to be larger than $0.06 \text{ GeV}/c$ in the barrel region ($-0.6235 < \cos \theta < 0.8332$, where θ is the polar angle opposite to the incident e^+ beam direction in the laboratory frame) and $0.1 \text{ GeV}/c$ in the endcap

region ($-0.8660 < \cos \theta < -0.6235$, and $0.8332 < \cos \theta < 0.9563$). The energies of photon candidates are required to be larger than 0.1 GeV in both regions.

To select τ -pair samples, we require four charged tracks with zero net charge and a total energy of charged tracks and photons in the center-of-mass (CM) frame less than 11 GeV. Furthermore, the missing momentum in the laboratory frame is required to be greater than 0.1 GeV/ c and its direction to be within the detector acceptance, where the missing momentum is defined as the deficit of sum of the observed momentum vectors from that of the initial e^+e^- system. We also require $\cos \theta_{\text{thrust-miss}}^{\text{CM}} < -0.6$ to reduce $q\bar{q}$ backgrounds, where $\theta_{\text{thrust-miss}}^{\text{CM}}$ is an opening angle between the thrust axis and the missing momentum in CM frame. The event is subdivided into 3-prong and 1-prong hemispheres according to the thrust axis in the CM frame. These are referred to as the signal and tag side, respectively.

In order to remove the dominant $q\bar{q}$ background, we require that the lepton probability $P_{\mu/e}$ be greater than 0.1 and that the invariant mass of the particles on the tag side be less than 1.8 GeV/ c^2 ($\simeq m_\tau$). Similarly, we require that both kaon daughters of the ϕ candidate have kaon probabilities $P_K > 0.8$. The effective mass of the signal side must be less than 1.8 GeV/ c^2 . Here P_ℓ is the likelihood that a charged particle is of type ℓ ($\ell = \mu$ or e or K or π), defined as $P_\ell = L_\ell / (L_\ell + L_x)$, where L_ℓ and L_x are the likelihoods of the particle for ℓ and other species hypotheses, respectively, determined from responses of the relevant detectors. We allow at most one photon on the tag side to take account of initial state radiation, while requiring no extra photons on the signal side.

Candidates ϕ mesons are reconstructed using oppositely charged kaons within the barrel and forward endcap region. To suppress combinatorial backgrounds from other τ decays and $q\bar{q}$ processes, we require that the ϕ momentum be greater than 1.5 GeV/ c in the CM frame. After these requirements the remaining contributions from $B^0\bar{B}^0$, B^+B^- , Bhabha, μ pair and two photon backgrounds are negligible.

To separate $\phi K^\pm \nu$ from $\phi \pi^\pm \nu$, the remaining charged track is required to satisfy the same kaon identification criteria as the ϕ daughters. The $\tau\tau$ and $q\bar{q}$ contributions are reduced by requiring the opening angle ($\theta_{\phi K}^{\text{CM}}$) between ϕ and K^\pm in the CM frame to satisfy $\cos \theta_{\phi K}^{\text{CM}} > 0.92$ and the momentum of the ϕK^\pm system in the CM frame must be greater than 3.5 GeV/ c . For $\phi \pi^\pm \nu$, we require the charged track to be identified as a pion, $P_\pi > 0.8$, and the opening angle between ϕ and π^\pm in the CM frame to satisfy $\cos \theta_{\phi \pi}^{\text{CM}} < 0.98$.

Fig.1(a) shows the K^+K^- invariant mass distribution after all $\tau^\pm \rightarrow \phi K^\pm \nu$ selection requirements. While there are two possible K^+K^- combinatorial contributions from $K^\pm K^\mp K^\pm$ on the signal side in forming a ϕ meson; all combinations are included. Non-resonant backgrounds are mostly attributed to $\tau^\pm \rightarrow K^+K^-\pi^\pm \nu$ events with $B = (1.55 \pm 0.07) \times 10^{-3}$. Very small contributions are expected from $q\bar{q}$ processes.

SIGNAL AND BACKGROUND EVALUATION

The detection efficiencies ϵ for $\tau^\pm \rightarrow \phi K^\pm \nu$, $\phi K^\pm \pi^0 \nu$ and $\phi \pi^\pm \nu$ are evaluated, as listed in Table I, from MC using KKMC [6], where the $V-A$ interaction is assigned on the vertices and the final hadrons decay according to non-resonant phase space. The signal $\tau^\pm \rightarrow \phi K^\pm \nu$ detection efficiency is $\epsilon_{\phi K \nu} = (1.82 \pm 0.01)\%$, including the branching fraction of $\phi \rightarrow K^+K^-$.

Signal yields are evaluated by a fit to a p-wave Breit-Wigner (BW) distribution, convoluted with a Gaussian function (of width σ) to account for the detector resolution. The ϕ width is fixed to be $\Gamma_\phi = 4.26$ MeV (PDG value [7]), but σ is allowed to float. From fits to

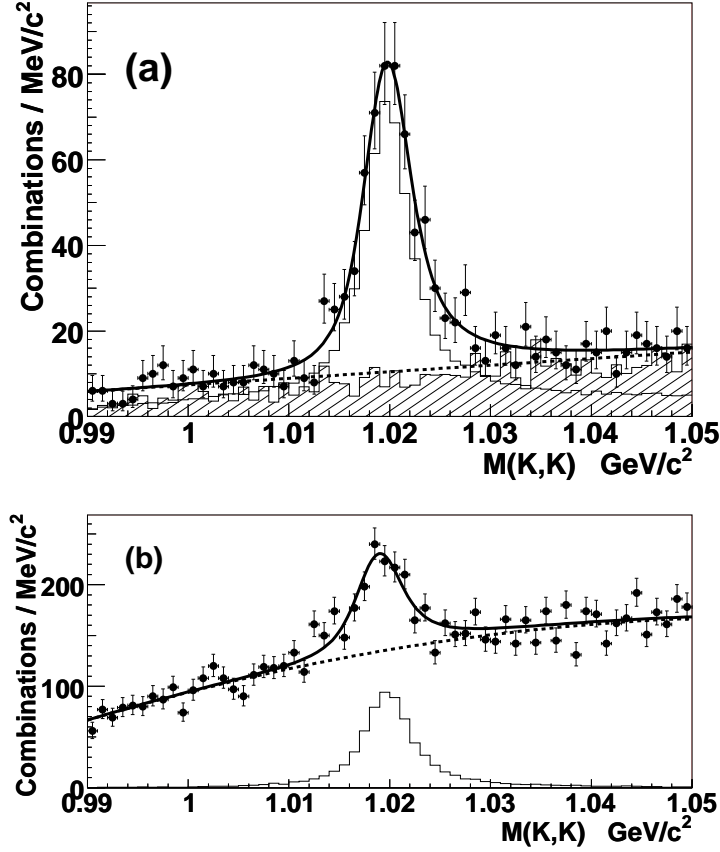


FIG. 1: K^+K^- invariant mass distributions for (a) $\tau^\pm \rightarrow \phi K^\pm \nu$ and (b) $\tau^\pm \rightarrow \phi \pi^\pm \nu$. Points with error bars indicate the data. The hatched histograms show the expectations from $\tau^+\tau^-$ and $q\bar{q}$ background MCs. The open histogram is the signal MC with $B(\tau^\pm \rightarrow \phi K^\pm \nu) = 4 \times 10^{-5}$ in (a) and $B(\tau^\pm \rightarrow \phi \pi^\pm \nu) = 6 \times 10^{-5}$ in (b). The curves show the best fit results. See the text for details.

TABLE I: Detection efficiencies ϵ and cross-feed rates (%).

Candidates	Decay modes		
	$\phi K \nu$	$\phi \pi \nu$	$\phi K \pi^0 \nu$
$\tau \rightarrow \phi K \nu$	1.823 ± 0.009	0.049 ± 0.002	0.327 ± 0.006
$\tau \rightarrow \phi \pi \nu$	0.110 ± 0.002	1.660 ± 0.014	0.009 ± 0.001

signal MC, the ϕ mass detector resolution is found to be, $\sigma = 1.07 \pm 0.03 \text{ MeV}/c^2$, which is consistent with the fit result to the data of $1.2 \pm 0.3 \text{ MeV}/c^2$.

The K^+K^- invariant mass distributions for $\tau^\pm \rightarrow \phi K^\pm \nu$ and $\phi \pi^\pm \nu$ candidates are fitted with a p-wave BW distribution plus a linear and a second order polynomial background function, respectively, as seen in Figs. 1(a) and (b). The obtained signal yields are $N_{\tau \rightarrow \phi K \nu} = 573 \pm 32$ and $N_{\tau \rightarrow \phi \pi \nu} = 753 \pm 84$.

MC studies show that only $\tau^\pm \rightarrow \phi \pi^\pm \nu$, $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ and $q\bar{q}$ samples yield significant contributions peaking at the ϕ mass. The contribution of other backgrounds is less than 0.01% and can be neglected. The number of $\tau^\pm \rightarrow \phi \pi^\pm \nu$ events in the data is already

evaluated. Other contributions are estimated below.

In order to evaluate the branching fraction and background contribution from $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$, we select $\pi^0(\rightarrow \gamma\gamma)$ candidates and combine them with $\phi K^\pm \nu$ combinations that satisfy the requirements listed above. The signal yield is estimated by fitting its $K^+ K^-$ invariant mass distribution with a p-wave BW distribution plus a linear background function, as shown in Fig.2. The resulting yield is $8.2 \pm 3.8 \phi K \pi^0 \nu$ events in data. With the detection efficiency of $\epsilon_{\phi K \pi^0 \nu} = (0.395 \pm 0.007)\%$ evaluated by MC and the produced number of $\tau\tau$'s, $N_{\tau\tau} = 401.4 \text{ (fb}^{-1}) \times 0.892 \text{ (nb)} = 3.58 \times 10^8$, we obtain a branching fraction of

$$B(\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu) = (2.9 \pm 1.3 \pm 0.2) \times 10^{-6} \quad (1)$$

with a systematic uncertainty of 6.9%, which is described later. Using this we estimate the contamination of $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ events in the $\tau^\pm \rightarrow \phi K^\pm \nu$ signal as $N_{\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu}^{\text{cont}} = (6.8 \pm 3.1)$ events, given the cross-feed rate of $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ to the $\tau^\pm \rightarrow \phi K^\pm \nu$ signal to be $(0.327 \pm 0.006)\%$, as listed in Table I.

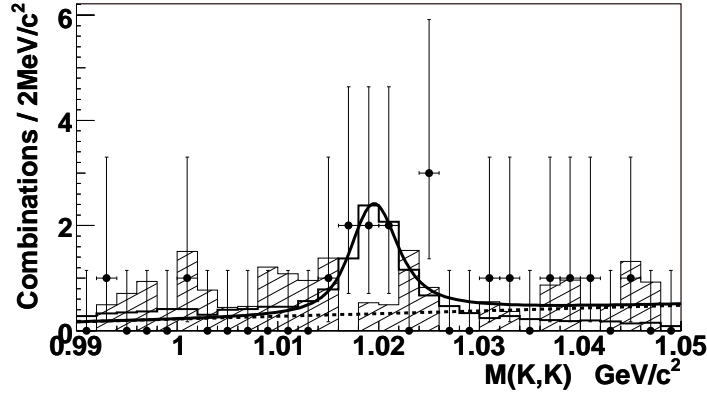


FIG. 2: $K^+ K^-$ invariant mass distributions for $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$. Points with error bars indicate the data. Histograms show the MC expectations of τ -pairs (hatched) and signal (white) with a branching ratio of 3×10^{-6} .

From the MC (731.1 fb^{-1}) study, we find the contamination of $q\bar{q}$ is $N_{q\bar{q}} = 12.1 \pm 4.5$. To take into account the uncertainty in ϕ production in $q\bar{q}$ MC, we compare MC results with enriched $q\bar{q}$ data by demanding that the effective mass of the tag side be larger than $1.8 \text{ GeV}/c^2$. With this selection, the background is $q\bar{q}$ dominated and the other backgrounds are negligible. The yield in data is 262 ± 21 events and 117.4 ± 9.9 events for $q\bar{q}$. We then scale the above estimate by the factor, $f = 2.23 \pm 0.47$, and obtain the $q\bar{q}$ contamination, $N_{q\bar{q}}^{\text{cont}} = 14.8 \pm 3.5$ events.

RESULTS

The peaking backgrounds described above, $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ and $q\bar{q}$, are subtracted from the signal yield, $N_{\tau^\pm \rightarrow \phi K^\pm \nu} = (573 \pm 32) - (6.8 \pm 3.1) - (14.8 \pm 3.5) = 551.4 \pm 32.3$ events. To take into account cross-feed between $\tau^\pm \rightarrow \phi K^\pm \nu$ and $\tau^\pm \rightarrow \phi \pi^\pm \nu$ due to particle misidentification ($K \leftrightarrow \pi$), we solve the following simultaneous equations,

$$N_{\phi K \nu} = 2N_{\tau\tau} \left(\epsilon_{\phi K \nu} \times B_{\phi K \nu} + \epsilon_{\phi \pi \nu}^{\phi K \nu} \times B_{\phi \pi \nu} \right), \quad (2)$$

$$N_{\phi\pi\nu} = 2N_{\tau\tau} \left(\epsilon_{\phi K\nu}^{\phi\pi\nu} \times B_{\phi K\nu} + \epsilon_{\phi\pi\nu} \times B_{\phi\pi\nu} \right), \quad (3)$$

where $B_{\phi K\nu}$ and $B_{\phi\pi\nu}$ is the branching fraction for $\tau^\pm \rightarrow \phi K^\pm \nu$ and $\tau^\pm \rightarrow \phi \pi^\pm \nu$, respectively. ϵ 's are the detection efficiencies listed in Table I. $\epsilon_{\phi K\nu}^{\phi\pi\nu}$ is the efficiency for reconstructing $\tau^\pm \rightarrow \phi K^\pm \nu$ as $\tau^\pm \rightarrow \phi \pi^\pm \nu$ while $\epsilon_{\phi\pi\nu}^{\phi K\nu}$ is the efficiency for reconstructing $\tau^\pm \rightarrow \phi \pi^\pm \nu$ as $\tau^\pm \rightarrow \phi K^\pm \nu$. The resulting branching fraction for $\tau^\pm \rightarrow \phi K^\pm \nu$ is

$$B_{\phi K^\pm \nu} = (4.06 \pm 0.25) \times 10^{-5}, \quad (4)$$

where the uncertainty is calculated with only statistical ones of $N_{\phi K\nu}$ and $N_{\phi\pi\nu}$. The uncertainty in the detection efficiencies, ϵ 's, will be taken into account in the systematic error. $B_{\phi\pi\nu}$ is obtained by the same way as

$$B_{\phi\pi\nu} = (6.07 \pm 0.71) \times 10^{-5}, \quad (5)$$

but this is not the final branching fraction for the decay since the unknown contamination of $\tau \rightarrow \phi(n\pi)\nu$ ($n \leq 5$) decays still must be subtracted.

Systematic uncertainties are estimated as follows: Evaluation uncertainties of the integrated luminosity, $\tau\tau$ cross-section and trigger efficiency are 1.4%, 1.3% and 1.1%, respectively. Track finding efficiency has an uncertainty of 4.0%. Uncertainties in lepton and kaon identification efficiencies and fake rate are evaluated, respectively, to be 3.2% and 3.1% by averaging the estimated uncertainties depending on momentum and polar angle of each charged track. To evaluate the systematic uncertainty of fixing Γ_ϕ in the BW fit, we calculate the change in the signal yield when Γ_ϕ is varied by ± 0.05 MeV (the uncertainty quoted by PDG) [7]: The uncertainty is 0.2%. The branching ratio for $\phi \rightarrow K^+ K^-$ gives an uncertainty of 1.2% following the PDG [7]. The backgrounds from $N_{\phi K^\pm \nu}$ and $N_{\phi \pi^\pm \nu}$ have uncertainties of 0.3% and 0.4%, respectively. The signal detection efficiency $\epsilon_{\phi K\nu}$ has an uncertainty of 0.5%. A total systematic uncertainty of 6.5% is obtained by adding all uncertainties in quadrature. The resulting branching fraction is then

$$B(\tau^\pm \rightarrow \phi K^\pm \nu) = (4.06 \pm 0.25 \pm 0.26) \times 10^{-5}. \quad (6)$$

The systematic uncertainties for $\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu$ are similar to those for $\tau^\pm \rightarrow \phi K^\pm \nu$. The main differences are on the trigger efficiency of 0.3%, the detection efficiency $\epsilon_{\phi K\pi\nu}$ of 1.8% and the π^0 detection efficiency of 1.7%. Those provide a total systematic uncertainty of 6.9%, and the branching fraction of

$$B(\tau^\pm \rightarrow \phi K^\pm \pi^0 \nu) = (2.9 \pm 1.3 \pm 0.2) \times 10^{-6}. \quad (7)$$

Finally, we examine a possible resonance state that intermediates the final ϕK^\pm hadronic system. CLEO [1] assumed a resonance having a mass of 1650 MeV/ c^2 with a width of 100 MeV/ c^2 in the evaluation of their detection efficiency for $\tau^\pm \rightarrow \phi K^\pm \nu$, however no signal was found. We generate a resonant MC with the KKMC simulation program. The weak current is generated with a $V - A$ form while the ϕK^\pm system is assumed to be produced from a 2-body decay of a resonance. In Fig. 3(a), the ϕK^\pm mass distribution for data is compared to MC; the combinatorial background is subtracted using the $K^+ K^-$ sideband. Fig. 3(b) shows the ϕ 's angular distribution in the ϕK^\pm rest frame ($\cos \alpha$), where the momentum direction of ϕK^\pm in the laboratory frame ($P(\phi + K)$) is taken as the reference axis. It indicates an isotropic distribution in the ϕK^\pm system. For both the invariant mass and

angular distributions of ϕK^\pm system, the phase space MC reproduces the signal distribution well. On the other hand, the 1650 MeV/ c^2 state, indicated by the dotted histogram in Fig. 3(a), clearly cannot account for the entire signal. Assuming resonant production, the best agreement with the data is found for a mass and a width of $\simeq 1570$ MeV/ c^2 and $\simeq 150$ MeV/ c^2 , respectively, as shown by the dot-dashed histogram. However, since the shape of the resonant MC is similar to the phase space distributed MC, it is inappropriate to look for the intermediate resonance state with $\Gamma \sim O(100\text{MeV})$ in this narrow mass range of ~ 250 MeV/ c^2 . In fact, the phase space distribution (the open histogram) agrees well with data.

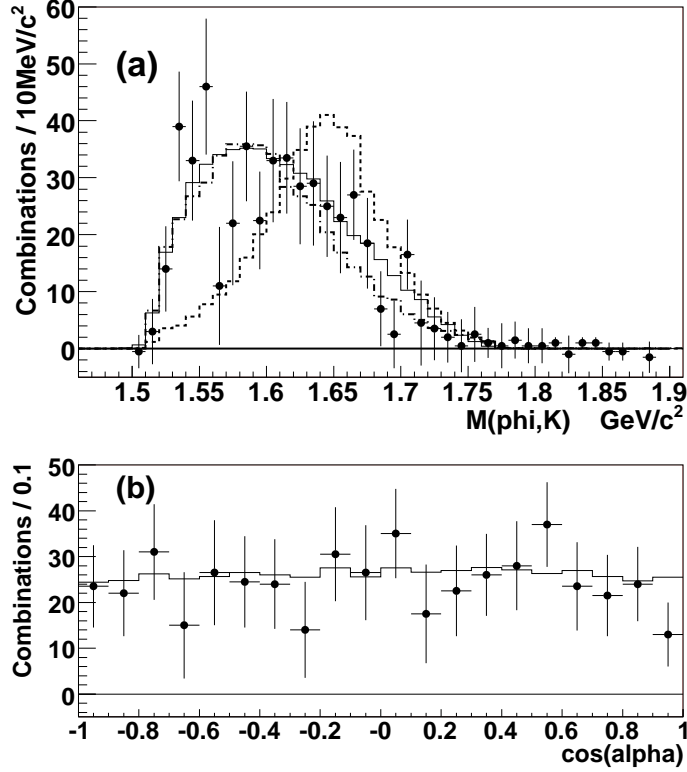


FIG. 3: (a) invariant mass and (b) angular distributions for ϕK^\pm system. The non- ϕ -resonant backgrounds are subtracted using the sideband spectra. Points with error bars indicate the data. Open histogram shows the phase space distributed signal MC, and dotted and dot-dashed histograms indicate the signal MC mediated by a resonance with $M = 1650$ MeV/ c^2 and $\Gamma = 100$ MeV/ c^2 and $M = 1570$ MeV/ c^2 and $\Gamma = 150$ MeV/ c^2 , respectively. In MC, the branching ratio of 4×10^{-5} is assumed. (b) ϕ 's angular distribution in the ϕK^\pm rest frame, where the direction of $P(\phi + K)$ in the laboratory frame is taken as the reference axis.

CONCLUSION

Using a 401 fb^{-1} data sample, we report the first observation of the rare τ decay mode, $\tau^\pm \rightarrow \phi K^\pm \nu$, with a branching fraction of

$$B(\tau^\pm \rightarrow \phi K^\pm \nu) = (4.06 \pm 0.25 \pm 0.26) \times 10^{-5}. \quad (8)$$

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